SUPERCONDUCTIVE HOT-ELECTRON BOLOMETER MIXERS

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ABSTRACT

Hot electron bolometer (HEB) mixers have made exceptional progress in recent years. These superconductive devices can operate well above the energy gap where current state-of-the-art SIS mixers begin to fail. Mixing results have been reported throughout the submillimeter range, up to several THz. The bolometer consists of a simple nanobridge that is biased near the center of the superconductive transition. Only about 0.1μW of LO power is required. HEB mixers are expected to play a central role in astrophysical observations at THz frequencies and are currently under development for ground, aircraft, and space-borne observatories. This paper gives a short introduction to these unique sensors, a brief survey of the current status of the field, and some discussion of important topics related to future development.

INTRODUCTION

As discussed in several papers at this workshop, there is clearly a need for very-low noise heterodyne sensors for submillimeter-wave astronomy applications. Currently SIS quasiparticle mixers fabricated from Nb or NbTiN provide state-of-the-art performance for frequencies up to about 1.2 THz. An SIS tunnel junction has a large capacitance which must be tuned out by the mixer circuit to avoid shunting the signal away from the device. Losses in the superconductive mixer embedding circuit limit the best performance to frequencies less than the gap frequency, $f_{gap} \approx 2\Delta/h$. For spectroscopy at THz frequencies above f_{gap}, an alternative is a mixer based on an ultra-fast, low-noise hot-electron bolometer[1,2] (HEB). Bolometers have been used occasionally over the years as heterodyne mixers primarily because of their low-noise and ability to operate at very high frequencies. Unlike an SIS mixer, the predicted conversion efficiency, LO power, and noise temperature are independent of frequency. The principle disadvantage of a bolometer mixer is the slow thermal response time, τ_{th}, which limits the intermediate frequency (IF) to low values, usually of order MHz. This is too low to be useful for many practical spectroscopy applications which generally require several GHz of IF bandwidth. The HEB mixer addresses this issue: the thermal response time is short enough, a few 10's of picoseconds, to provide IF up to several GHz.

Figure 1 shows the basic geometry of the HEB device. It consists of a thin-film nanobridge of superconductor with thick normal-metal contacts at each end, at a bath temperature T_b. These contacts connect to the planar antennas and transmission lines of an integrated embedding circuit, to provide efficient coupling of radiation to the device. To operate a bolometer in a heterodyne mode, a local oscillator (LO) voltage at frequency ω_{LO} and a signal voltage at frequency ω_s are applied to the device: $V(t) = V_{LO}\cos(\omega_{LO}\, t) + V_s\cos(\omega_s\, t)$. The power dissipated in the film is $P(t) = V(t)^2/R_N$ where R_N is the normal state resistance. Substituting for V(t) and carrying out the algebra, one finds the time dependent term, $2(P_{LO}P_s)^{1/2}\cos(\omega_{IF}t)$, where $\omega_{IF} = \omega_{LO} - \omega_s$, is the difference or intermediate frequency, P_{LO} and P_s are the LO power and signal power respectively dissipated in the bolometer. The bolometer is not fast enough to follow the rf, so the power dissipated at these frequencies is the time averaged value. (In practice, the DC bias and LO power are used to heat the electrons from T_b up to the transition

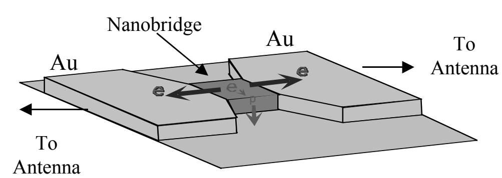

Fig.1 Basic geometry of the HEB mixer device.

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temperature, T_C). The voltage responsivity, S, of the bolometer[3] can be used to estimate the IF voltage amplitude as $V_{IF} = S \bullet 2(P_{LO}P_s)^{1/2}$. The responsivity is given by: $S = I\,(dR/dT) / [G\bullet(1 + \omega_{IF}^2\,\tau_{th}^2)^{1/2}]$ where dR/dT is the derivitive of film resistance with temperature, and G is the thermal conductance. τ_{th} is the thermal response time and is equal to C_e/G, where C_e is the specific heat of the electrons. Thus for low enough IF, that is $\omega_{IF}^2\,\tau_{th}^2 < 1$, the bolometer can follow the IF power swing. To achieve a fast response time, the thermal conductance for the hot electrons must be high. This is achieved in one of two ways: either by production of phonons which carry the heat to the substrate (the *phonon-cooled* HEB mixer[1]); or by the diffusion of hot electrons out the ends of the bridge (the *diffusion-cooled* HEB mixer[2]). Each will be briefly described below with some examples of recent results.

Phonon-Cooled HEB Mixer

The phonon-cooled HEB mixer was first proposed in 1990[1]. In this case, the energy deposited into the electron subsystem by the LO and signal radiation and the dc bias current is removed by means of electron-phonon collisions and the subsequent escape of nonequilibrium phonons into the substrate (see fig. 1). The phonon escape time, τ_{es} , is proportional to the film thickness, and must be much shorter than the phonon-to-electron energy transfer time, τ_{pe} , (and the electron-phonon time τ_{ep}) At helium temperatures a□□□□□ very thin films, $\tau_{es} \ll \tau_{pe}$, τ_{ep} and hence all the energy is transferred from electrons to the substrate. The 3-dB IF bandwidth for this type of mixer is $f_{3dB} = 1/(2\pi\tau_{ep})$.

Phonon-cooled operation was successfully implemented in Nb films with thickness d<10 nm[1,4]. However, $\tau_{ep} \sim 2$ ns in Nb which gives $f_{3dB} \approx 80$ MHz; this is too low to be useful for most practical applications. The same applies for most other superconducting materials. Niobium nitride is the only material known which has a short enough electron-phonon time[5], $\tau_{ep} \sim 20$ ps, to provide a useful IF. For the thinnest NbN films used to date, (thickness ≈ 3 nm), the highest IF bandwidths measured are about 5 GHz[6]. Any further increase of bandwidth in NbN seems to be problematic because of the difficulty of fabricating even thinner (<3 nm) high-quality NbN films. The high sheet resistance, R_S, of NbN requires a device geometry of less than 1-square to provide a reasonable impedance match in a planar embedding circuit. A typical size is 1 μm wide by 0.1-0.3 μm long. This also helps reduce the LO power requirement, which is proportional to the device volume. In addition, since $\tau_{ep} \propto T^{-2}$, higher T_C leads to a higher IF bandwidth. However, the mixer noise temperature[7] T_M is predicted to be proportional to T_C, so this type of device may have to trade-off mixer noise for IF bandwidth. NbN HEB mixers have been extensively studied and measured at a variety of frequencies up to several THz [8-11].

Diffusion-Cooled HEB Mixer

The unique feature of this device, which was first proposed in 1993[2], is that it uses the rapid diffusion of hot electrons out of the ends of the nanobridge into the normal metal contacts to provide a high thermal conductance (see fig. 1). In order for diffusion to dominate over the electron-phonon cooling mechanism, the nanobridge must be short: $L \leq 2(D\,\tau_{ee})^{1/2}$ where D is the diffusion constant, and τ_{ee} is the electron-to-electron energy exchange time. Basically as electrons absorb energy from the rf field, they share that energy in a time τ_{ee} and also diffuse a distance L/2, at which point, they encounter the normal metal contacts which serve as a heat sink. For 10 nm Nb films, L turns out to be typically 0.1-0.3 μm. The thermal response time is given by $\tau_{th} = L^2/\pi^2\bullet D$, which gives an IF bandwidth $f_{3dB} = \pi\bullet D/(2\bullet L^2)$. For submicron Nb bridges, IF bandwidths of several GHz are possible. For a given film sheet resistance, R_S, the length of the bridge determines the IF bandwidth and the width (typically 0.1-0.2μm) can be varied to obtain a good impedance match to the mixer embedding circuit. A diffusion-cooled HEB mixer was first demonstrated at high frequencies with a Nb device[12], and the transition from the phonon-cooling to the diffusion-cooling mechanism was shown with NbC[13] and Nb[14]. The L^{-2} dependence of the IF bandwidth has been measured at microwave and submillimeter-wave frequencies [14,15]. An IF bandwidth up to 9 GHz has been achieved, which is the largest measured to date[15].

The diffusion cooling regime can be achieved in many materials as long as the device is made sufficiently short. Fortunately, there is a variety of materials with large diffusivities, such as Nb, NbC, Ta, and Al. A large range of diffusion constants gives flexibility in adjusting the mixer resistance to a desirable value, since materials with different resistivities can be chosen. Thus a diffusion-cooled HEB mixer provides flexibility in the choice of materials. This is not the case for the phonon-cooled HEB mixer as discussed above. See reference 16 for a detailed discussion of the tradeoffs in choosing different materials.

Diffusion-cooled HEB mixers have now been tested in submillimeter wave heterodyne receivers at frequencies from 500 GHz up to 2.5 THz[17-19], using devices made from Nb. Figure 2 shows an SEM photo of a 2.5 THz Nb HEB mixer on a silicon chip[15,19]. The chip is glued to the back of a silicon lens to quasioptically couple the radiation into the twin-slot antenna. Similar schemes are used with NbN mixers. The *fixed-tuned* rf bandwidth of a similar 2.2 THz mixer was measured to be 1 THz, using a Fourier transform spectrometer[15]. The rf impedance of an HEB device is essentially real (practically no parasitic susceptances) which makes designing broadband embedding circuits an easier task than for SIS or Schottky devices. Other, lower T_C, materials including Al[20,21], Nb/Au-bilayers[22], and Ta[23] have also been recently investigated. The LO power is predicted to be proportional to T_C^2 and the noise temperature to T_C , and both of these proportionalities have been confirmed for Nb devices at microwave frequencies[22]. Thus lower T_C superconductors may offer important advantages in sensitivity and LO requirements.

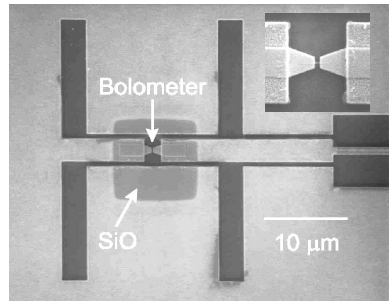

Fig. 2 SEM of Nb HEB mixer embedding circuit showing twin-slot antenna and CPW lines. Inset shows area around the submicon device.

DISCUSSION OF RESULTS

Quite a large number of groups are working on HEB mixers. Phonon-cooled mixers are being developed at the University of Massachusetts, the Harvard-Smithsonian Center for Astrophysics, the Moscow State Pedagogical University in Russia, Chalmers University of Technology in Sweden, the DLR Institute of Space Sensor Technology in Germany, and IRAM in France. Diffusion-cooled mixers are under development at the Jet Propulsion Laboratory, Yale University, the University of Colorado in collaboration with NIST, Delft University in collaboration with SRON in The Netherlands, and IRAM in France. This has lead to quite a few very good receiver results. Figure 3 shows a summary of some of these results. Also shown in the plot, for comparison, are state-of-the-art SIS and Schottky receiver results. As can be seen, HEB receivers perform well at THz frequencies where SIS mixers fail, and provide significantly lower noise than Schottky receivers at terahertz frequencies. In addition, a heterodyne receiver using a phonon-cooled HEB mixer was recently used for the first time to make practical radioastronomy observations[24]. Figure 4 shows the measured spectra of CO(9-8) at 1 THz. Further development and optimization will be required to see if either type of HEB mixer provides better overall performance.

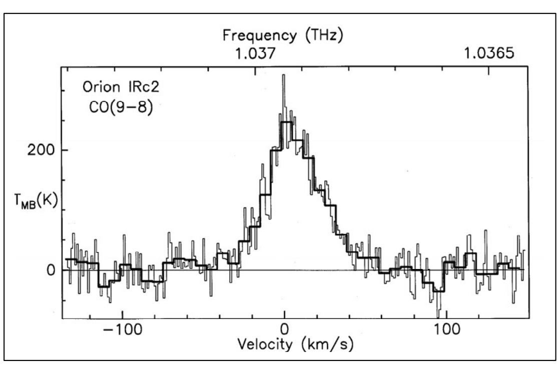

Fig. 4 A CO spectra of Orion obtained with an HEB receiver; from ref. 20.

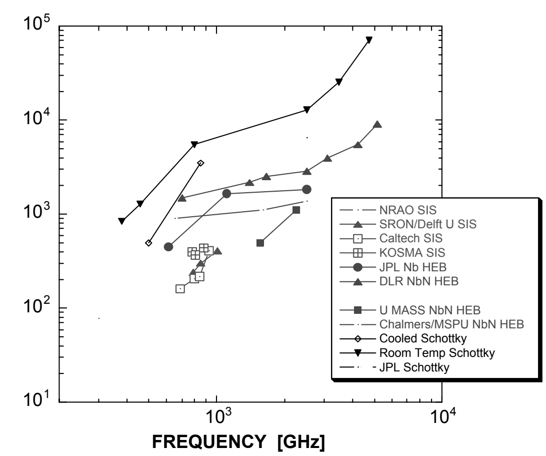

Fig.3 Smmary of receiver noise temperature vs. requency for HEB, SIS, and Schottky mixers.

HEB mixers typically require only about 20-100 nW of LO power (depending on the coupling losses to the device. The actual power absorbed in the device itself can be much less[15,17]). This is lower than any other mixer technology, which is an important advantage since LO power at THz frequencies is difficult to generate. Recently an HEB mixer was pumped for the first time by a compact, solid state LO source[25] at 1.5 THz. This source produced only a few microwatts, and the estimated power incident on the mixer was 80-100 nW.

CURRENT AND FUTURE APPLICATIONS

There are several current and planned instrument applications for HEB receivers at THz frequencies. One of the most visible efforts is the HIFI instrument for the Herschel Space Observatory. It will employ HEB mixers developed at JPL and Chalmers University to cover the frequency range 1.4 – 1.9 THz. This will allow for the observation of dozens of astrophysically important emission-lines including C+ at 1.9 THz and water lines near 1.6 THz. There are also two heterodyne instruments being built for NASA's Stratospheric Observatory for Infrared Astronomy. One instrument by the University of Cologne (called GREAT) will use HEB mixers to cover 1.6 to 1.9 THz. A second instrument (called CASIMIR) built by Caltech/JPL will ultimately use 1.5 – 3.0 THz HEB receivers. The University of Massachusetts is building a ground-based instrument, called TREND, for use at 1.3 – 1.5 THz on the AST/RO telescope at the South Pole[26].

There are also a few instruments in the planning or proposal stages. The Far Infrared Line Mapper (FILM) proposed out of JPL for a MIDEX flight opportunity will use diffusion-cooled HEB receivers at 1.4 THz and 1.9 THz to map N+ and C+ respectively in the Galactic plane[27]. An Ultra-Long Duration Balloon instrument called SMILES is current under study at JPL to use HEB mixers at 1.9 THz to survey C+ emissions[28]. There is also a concept for a Scanning Microwave Limb Sounder under study at JPL which will employ 2.0 – 2.5 THz HEB receivers to study several molecular species related to stratospheric chemistry, as well as cloud ice[29].

STATUS OF THEORY

This section will briefly survey the status of bolometer mixer theory. One of the most widely used bolometer theories is the so-called lumped-element model[7]. This is an analytical model which treats devices with a single uniform temperature for the hot electrons. Thus it is best suited to phonon-cooled HEB mixers. It includes thermal fluctuation and Johnson noise effects and electro-thermal feedback. It provides reasonable agreement for pumped IV curves, IF bandwidth, and LO power. However it over estimates the conversion efficiency and under estimates the mixer noise. A distributed temperature model for phonon-cooled devices was recently introduced[30]. It is essentially a modification of the lumped-element model to include nonuniform DC power dissipation along the bridge. It basically has the same successes and shortcomings as the lumped element model. For diffusion-cooled HEB mixers, a "frequency-domain" mixer theory has been developed[31]. This is a numerical model that discretizes the nanobridge, and uses the resistance-temperature curve of a device as an input. It accounts for the temperature profile along the bridge using the Wiedemann-Franz law to characterize the heat flow between the discretized segments. It includes thermal fluctuation and Johnson noise effects and electro-thermal feedback. It provides reasonable agreement for pumped IV curves, IF bandwidth, and LO power. However it also over estimates the conversion efficiency and under estimates the mixer noise. There is also a "hot-spot" model for diffusion-cooled devices[32]. It accounts for the temperature profile, but neglects the width of the superconducting transition and does not include electrothermal feedback.

Basically all these bolometer mixer models predict the mixer noise temperature to be a few times T_C. This violates the quantum-limit on mixer noise, $T=hf/k$ [33], which is frequency dependent. One possible source of error is that these theories make use of the accepted bolometer noise model[34] for direct detection which has no quantum limit[33], and apply it to a bolometer used a heterodyne mixer which does have a quantum limit. These theories also assume that the HEB resistance is a function only of the electron temperature, which is not quite true in real devices. Whatever the reason, without a correct noise theory, it is very difficult to know how to properly optimize a bolometer mixer.

SUMMARY AND FUTURE DIRECTIONS

In summary, HEB mixers provide a low-noise superconductive heterodyne sensor suitable for the demanding applications of submillimeter-wave astronomy. They can operate at frequencies well above 1 THz where current state-of-the-art SIS mixers begin to fail. However there are several important areas for future development. A more complete noise theory is needed (at least one that can pass the quantum-limit test). There is a need for a better understanding of the device physics, and more accurate mixer models (particularly for diffusion-cooled devices). More systematic tests of at least the existing models are also needed. The result of this will hopefully be better optimized HEB mixers with lower noise. This may allow HEB mixers to compete with SIS mixers below 1 THz. If HEB mixers are not ultimately competitive with SIS, they will not find widespread use. Due to the opacity of the atmosphere above about 900 GHz, HEB receivers will likely be employed primarily on aircraft, balloon, and space platforms where the atmosphere no longer presents a serious problem. However, this provides fewer opportunities compared with ground-based observations. In addition, there should be more development of new materials (Nb/Au-bilayers, Ta, MgB_2,…) which may provide for lower noise, lower LO power requirements, or broader IF bandwidths. Finally there should be more engineering effort on practical receivers and real field tests.

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